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A Comparison of VLF and 50 Hz Field Testing of Medium Voltage Cables

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1 Introduction

Underground cables are ubiquitous in modern distribution networks and are frequently tested in the field after leaving the factory. Tests are performed after installation, during commissioning and for maintenance to monitor insulation health. A cable test can identify weak spots so actions can be taken to prevent a failure during normal service. It can also provide asset managers with the information necessary to minimize capital expenditure [1].

Small defects in cable insulation can lead to premature degradation and failure. In cross linked polyethylene (XLPE) insulation, strings of growing water filled cavities or water trees can grow to eventually cause insulation breakdown [2] [3]. In paper insulated lead covered (PILC) cables, voids introduced by mechanical stresses [4] can also lead to failure. To detect these defects a cable is taken offline and energised above its rated voltage. A portable high voltage source is needed that can energise the large cable capacitance without drawing too much current from the supply.

Small DC test kits were commonly used for testing PILC cables [5] until it was found that the space charge accumulated during DC testing accelerated water tree growth in healthy XLPE insulation [6]. The most widely adopted solution over the past two decades is very low frequency (VLF) where the test frequency is reduced to between 0.01 Hz and 0.1 Hz [7]. The changing waveform polarity reduces the accumulation of space charge but it is still a compromise as it does not replicate in service conditions.

Research at the University of Canterbury has enabled portable 50 Hz testing, with partial core resonant transformers (PCRTX) [8] [9]. These devices have been used for many years to test generator stators around New Zealand [10] [11]. By inductively tuning a small transformer to resonate with the cable capacitance at 50 Hz the reactive power drawn by the cable is supplied by the transformer's own inductance rather than the supply. By using significantly less core steel and solid insulation, the PCRTX is portable enough for field testing purposes.

Most cable tests are accompanied by a diagnostic measurement such as partial discharge (PD) or tan δ. These tests employ sensitive instrumentation in order to quantify the health of the cable insulation. A good HV source should be relatively free of internal partial discharges to avoid distorting the measurements.

Although desirable, power frequency testing of MV cables is considered difficult or impossible by asset managers. This report assesses the performance and feasibility of the PCRTX as a power frequency cable testing kit. The results of condition monitoring tests conducted on aged cables are presented along with the differences in tan δ and PD readings.

2 Background

2.1 VLF Testing

The power required to energise a cable's capacitance is proportional to the test frequency. Compared to 50 Hz, a cable excited with VLF draws 500 to 5000 times less power. This means test kits can be made extremely small and light. VLF test kits have been thoroughly developed with on-board features for easier operation and are well supported by international standards [12]. The technology employed to generate the wave shape and reverse the polarity varies between electromechanical and solid state to achieve a sinusoidal waveform.

The use of VLF has generated controversy throughout the industry as to its effectiveness. VLF test kits stress different components of the cable insulation compared with 50 Hz testing. At lower frequencies the electric field stress is governed by the insulation resistivity more so than power frequencies where the permittivity is more important [13]. For withstand tests, higher voltages are required with VLF compared to power frequency. It has been reported that the growth rate of electrical trees is faster with VLF than at power frequency [4].

2.2 Power frequency testing

Power frequency test equipment is usually labelled as bulky and expensive [13]. To minimise their size and weight, resonant circuits are generally used. These can be either frequency tuned or inductively tuned to achieve parallel or series resonance. The input impedance of the exciting transformer is significantly larger at resonance and the supply is only powering the losses of the cable insulation and the resonant circuit. Field testing has been accomplished at high voltages but with extremely large equipment [14] [15]. Commercial equipment is usually truck mounted, and involves separate variable inductors and exciting transformers.

2.3 Partial Core Resonant Transformers

The PCRTX is a tuneable transformer that combines both variable inductor and exciting transformer to save weight. The outer limbs and connecting yokes of a traditional transformer are discarded and a single limb core is used with air completing the magnetic circuit. The PCRTX is an inductively tuned resonant test set. The inductance of the transformer is tuned by connecting or disconnecting winding sections or adjusting the air gap spacing within the core.

2.4 Tan Delta

Perfect insulation behaves like a capacitor where the voltage and current are phase shifted by 90°. The applied electric field acts only to polarize the dielectric and no resistive current conducts through the insulation. In reality, defects in the cable insulation result in an increase in resistive current. The dissipation factor or tan δ indicates the level of resistive losses within the insulation. With reference to Figure 1, tan δ can be expressed as:

$$\tan\delta = \frac{I_R}{I_C} = \frac{1}{\omega CR} \qquad (1)$$

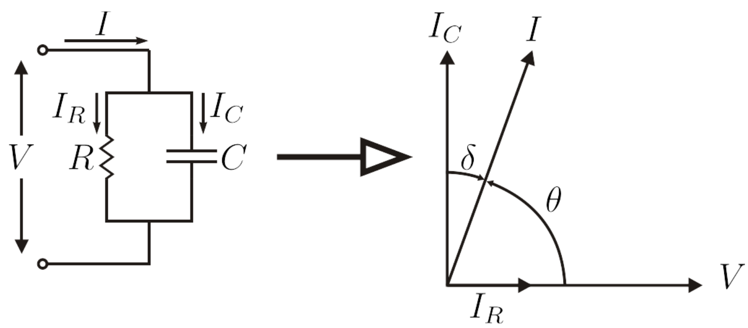

Figure 1: Tan delta and power factor angles

The measured value is dependent on different dielectric polarization processes occurring within the insulation. The polarization processes are frequency dependant and occur at different time scales [16].

The differential dissipation factor (DDF) or tan δ tip up is the increase in tan δ values as the test voltage is increased. In a new cable, the tan δ value should show a very small increase with voltage. Aged cable insulation exhibits a sharper increase in DDF with voltage.

2.5 *Partial Discharge*

Cable insulation can contain small voids of air. The electric field concentrates at voids due to a change in insulation permittivity and geometry. These non-uniformities are the sites of small gas discharges that partially bridge the gap between the earth screen and conductor. The electrons and ions produced by these localised discharges are distributed around the void's surface, further polarizing the insulation.

The equivalent circuit model of this physical phenomenon is shown in Figure 2 and involves the capacitance of the void C_V, the series capacitance between the void and the electrodes C_S and the parallel capacitance outside the void C_P. Every discharge within the void causes C_V to discharge through a finite resistance R_V.

Because this discharge current cannot be directly measured, a coupling capacitor C_C is connected in parallel with the cable under test. This stabilises the voltage during the PD pulse and supplies the current drawn by the discharge within the void. By integrating this current, a figure is obtained for the apparent charge released during a PD pulse.

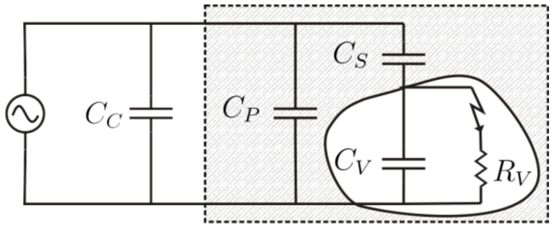

Figure 2: Basic PD test circuit

The apparent charge quantifies the extent of dielectric polarization causing a change in the cable capacitance [16] and not the number of charges released. The polarization of a dielectric is a frequency dependant quantity.

3 Equipment

The specifications of the VLF source and PCRTX used in the field tests are given in Table 1.

Table 1: Comparison of HV source specifications

	VLF	**50 Hz PCRTX**
Manufacturer	HV Inc	University of Canterbury
Model Number	VLF-4022CM(F)	PC1
Input	230 V, 6 A_{pk}, 50 Hz	230/400 V, 40 A_{pk}, 50 Hz
Output	44 kV, 0.1/0.05/0.02 Hz	20.7/36 kV, 50 Hz
Load Rating	1.1 µF @ 0.1 Hz, 5.5 µF @ 0.02 Hz	1.1 µF @ 36 kV, 2 µF @ 20 kV
Insulation	Liquid: Oil Immersed	Solid: NMN and Sylgard
Mechanism	Electromechanical polarity reversal, variable transformer	Partial core transformer, parallel resonant circuit
Weight	Control Unit: 23 kg HV Tank: 33 kg	Windings & Former: 120 kg Four Core Sections: 80 kg
Total Volume	0.1093 m^3	0.3244 m^3

3.1 VLF Test Kit

The VLF source used was a High Voltage Inc VLF-4022CM(F) as shown in Figure 3. The test kit consists of a control unit and a HV tank.

Figure 3: VLF control unit and HV tank

3.2 PCRTX

The PCRTX used for this test was PC1, shown on the left in Figure 4. This unit was designed for energising generator stators with high capacitance[10]. The input power can be taken from a line or phase voltage, preferably from a local service three phase supply. The test kit is split into the wound former and four individual core sections.

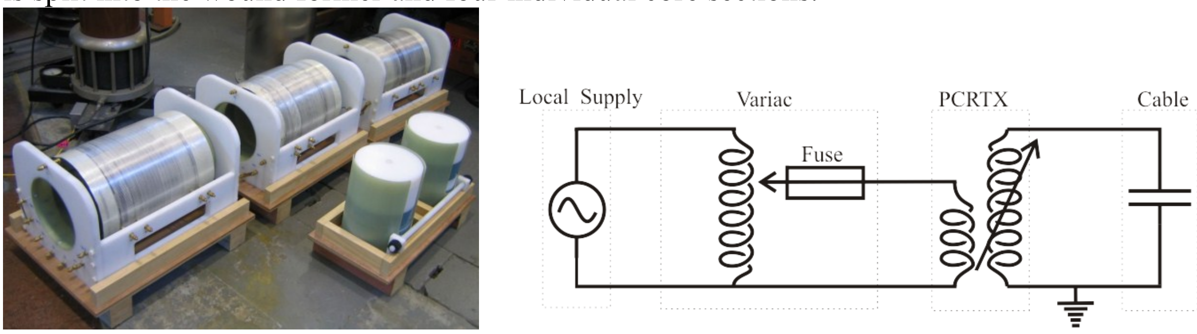

Figure 4: Three PCRTXs with core sections and test circuit

3.3 Instrumentation

The instrumentation was manufactured by Power Diagnostix and consists of a HV filter and a PD detector. Data is collected remotely via a fibre optic serial connection. The filter minimises the effect of source PD and the PD detector collects data on the apparent charge at each point of the sinusoidal cycle. The dissipation factor or tan δ is also measured simultaneously. Both the HV filter and PD detector can operate with any HV source.

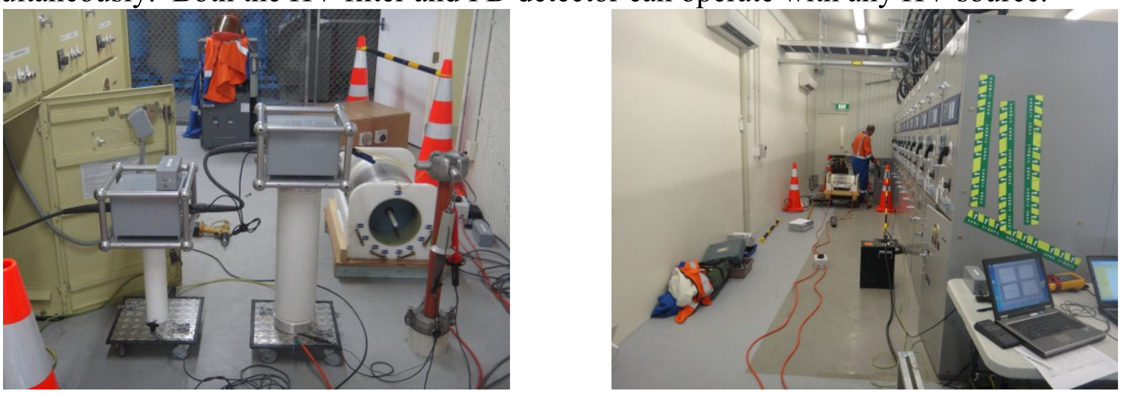

Figure 5: ICM Flex PD detector + filter and PCRTX at two cable testing sites

4 Method and Results

4.1 Test Procedures

4.1.1 Calibration

A PD calibrator is used to inject a known charge (2 nC to 10 nC) at the receiving end of the cable. This signal amplitude is about 125 V and oscillates at power frequency. The frequency is automatically determined by detecting the flicker rate of the lights with a photo diode. This calibrates the TDR to the length of the cable and also the PD sensor to a known charge.

4.1.2 Tuning

The PCRTX needs to be tuned to resonate with the cable capacitance at 50 Hz. A tuning diagram indicates the correct tap configuration and core spacing to achieve the desired inductance. The voltage is slightly increased to a few kV and the primary side power factor is measured. If it is leading or lagging significantly then more inductance needs to be added or removed by changing the tap configuration or the core spacing.

4.1.3 Measurements

A background PD reading was taken at 2 kV_{pk}. At this voltage most of the PD present is assumed to be from the environment, instrumentation and source. The voltage is steadily increased to find the PD inception voltage (PDIV). Finally tan δ and PD readings are taken at ½ V_0, V_0, 1½ V_0 and 2 V_0. The total test duration for each phase is approximately 15 mins.

4.2 Test Specimens

Tests were conducted on two 11 kV cables. Both cables were mostly PILC with intermittent sections of XLPE.

Table 2: Cable 1 specifications

Voltage Class	11 kV_{rms}	**Conductor Type**	Al/Cu
Conductor Size	300mm	**Capacitance**	0.65 μF
Insulation Type	98% PILC 2% XLPE	**Cable Length**	1242m
Test end termination	XLPE	**No. of joints**	8
Year Installed	1964	**Far end termination**	PILC

Table 3: Cable 2 specifications

Voltage Class	11 kV_{rms}	**Conductor Type**	Al/Cu
Conductor Size	300mm	**Capacitance**	0.767 μF
Insulation Type	93% PILC 7% XLPE	**Cable Length**	2050m
Test end termination	XLPE	**No. of joints**	17
Year Installed	1962	**Far end Termination**	PILC

Due to the technician's busy cable testing schedule the authors tested 2 phases of cable one and one phase of cable two. Discrepancies in the data collection procedure meant that the 1.5 U_0 readings were not recorded for the 50 Hz test on cable two.

4.3 Results

The tan δ measurements were clearly different for the two HV sources as shown in Figure 6. The values were generally an order of magnitude greater for the VLF source than the 50 Hz source. The VLF test showed a decrease in tan δ as the voltage was increased, whereas there was an increase in tan δ with voltage for the 50 Hz test.

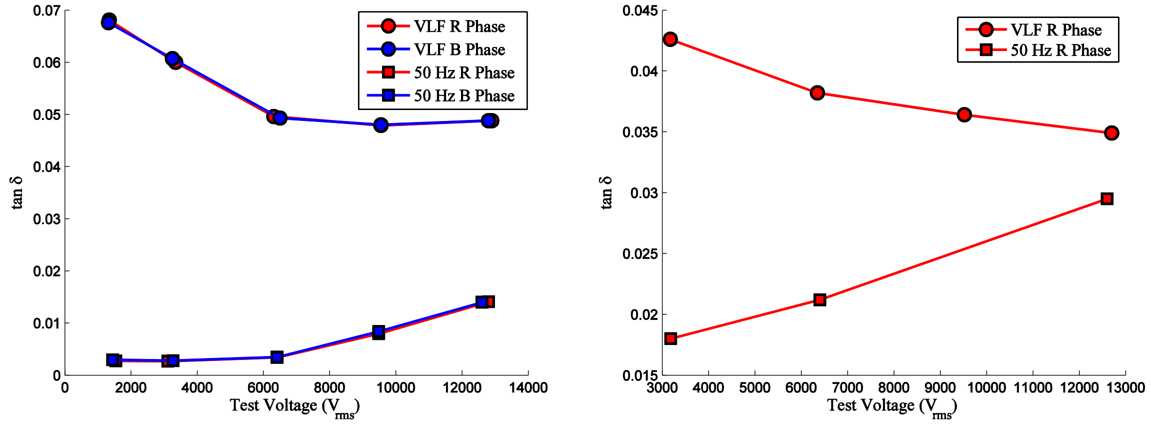

Figure 6: Cable one and cable two tan delta measurements for 50 Hz and VLF excitation

The peak values of PD were similar for both sources below rated voltage as shown in Figure 7. Above rated voltage the 50 Hz source showed a larger amount of PD than the VLF source. The sharp rise in PD coincided with the significant tip up in tan δ for the 50 Hz source. VLF PD readings levelled off after $1.5U_0$ and even decreased at $2U_0$ in the case of the red phase on cable one.

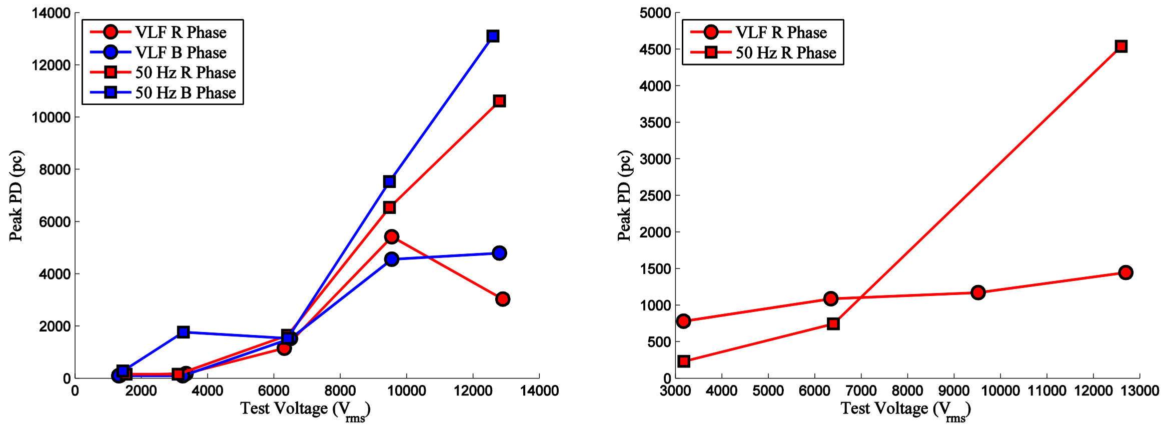

Figure 7: Cable one and cable two peak PD

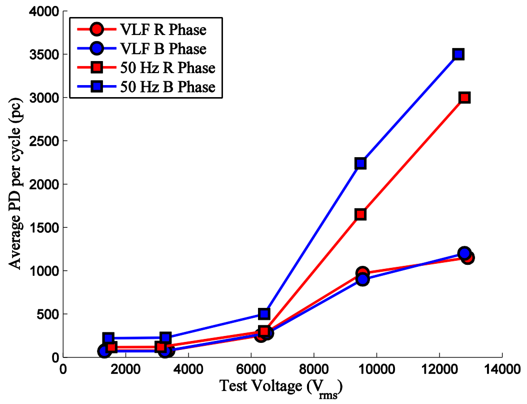

Figure 8: Average PD for cable 1

The average PD recorded per cycle for cable one is shown in Figure 8. The readings are consistent with the peak PD measurements and show significantly more PD at 50 Hz above the rated voltage. Table 4 shows that no trend was observed in PDIV although it was under rated voltage for both cables.

Table 4: Measured partial discharge inception voltage

Test Specimen	50 Hz PDIV(kV_{pk})	VLF PDIV (kV_{pk})
Cable 1 R Phase	5.8	5.5
Cable 1 B Phase	4.7	6
Cable 2 R Phase	6	4.75

The PCRTX was coarsely tuned in a matter of minutes with only adjustments to the tapping sections. The maximum current drawn from the supply was 7.75 A to energise a 0.65 μF cable and 13 A to energise a 0.767 μF cable as shown in Table 5. The PCRTX was not finely tuned in either of the tests because the level of tuning was adequate for the distribution board supply rating. Had it been precisely tuned, the input power factor would be closer to unity and the supply current drawn would have been even lower.

Table 5: Input current, input power factor and VA gain at $2U_0$ (12.7 kV) for the PCRTX

Test Specimen	C (nf)	I_{in}(A)	PF	VA Gain
Cable 1 R Phase	767	13	0.83	20
Cable 1 B Phase	768	12.3	0.85	21
Cable 2 R Phase	660	7.75	0.76	30

At the maximum test voltage the VA supplied to the load exceed the VA drawn from the supply by a factor of between 20 and 30. The PCRTX slightly detuned itself as the voltage was raised. This can be caused by a slight change in load capacitance due to partial discharge and mechanical forces within the PCRTX acting to center the core

5 Discussion

The diagnostics discussed in this paper are all affected by dielectric polarization. This occurs through many different mechanisms and all of them are frequency dependant [16]. Fundamentally VLF testing stresses different components of cable insulation than does 50 Hz testing. Low frequency electric fields stress the resistance of the insulation and at higher frequencies the capacitance plays a more important role [13]. The cable tan δ is a measure of resistive power loss which explains why tan δ was an order of magnitude higher at VLF than 50 Hz. Researchers have noted that VLF is more sensitive to water tree ingress [12].

The reason the tan δ readings at low frequencies tip down with increasing voltage is unknown. At 50 Hz, a tip up in the DDF is expected and often seen when testing transformer insulation. The tip up in tan δ values observed during the 50 Hz test coincided with an increase in partial discharge which was expected.

The mechanical voltage reversal of the VLF test kit produced visible PD on the screen every half cycle and the waveform produced was not entirely sinusoidal. There are VLF test kits available that use advanced solid state waveform generators and produce a cleaner and more ideal sinusoid. The authors suspect that some of the PDIVs detected under VLF were due to noise from the test kit and not PD from the cable. This explains why no consistent difference in PDIV was observed between the two sources. Other researchers have found the PDIV at 50 Hz to be approximately 80% of the PDIV at VLF [17].

Whilst conducting measurements, the 50 Hz test results stabilised quicker than the VLF measurements. The 10 second period of each VLF cycle meant the technician had to wait for at-least one minute longer to obtain enough data to get a stable reading.

Determining the health of the XLPE insulation in hybrid cables was impossible. The large amount of PD generated by the PILC cables completely masked the small amount of PD from the XLPE. A PD test on such an old PILC cable is inconclusive and for 11 kV cables factory PD testing is not required. Diagnostic measurements are most conclusive when compared to previous tests on the same cable. Unlike VLF tests, 50 Hz tan δ tests can be directly compared to an AS/NZ 1026 compliant factory test as shown in Figure 9.

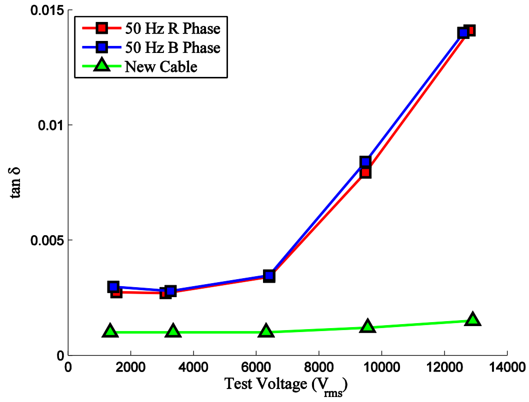

Figure 9: 50 Hz tan delta test compared to a factory test

6 Conclusion

A series of PD and tan δ tests were conducted on 11 kV cables with both a VLF and a 50 Hz HV source. This research was aimed at illustrating the difference between the two methods and assessing the feasibility of the partial core resonant transformer as a portable 50 Hz test kit. The cables had hybrid PILCA/XLPE insulation systems and were up to 2 km in length.

Tan δ values measured at VLF were an order of magnitude higher than those at 50 Hz. The VLF test displayed a negative DDF whilst the 50 Hz test showed a positive tip up tan δ characteristic. The 50 Hz test showed more PD than the VLF test which was expected but no consistent difference was observed between the PDIVs.

The PCRTX proved to be suitable for field testing cables. All the equipment was light enough to be carried in and small enough to be set up in a confined space. With a trained technician, the tuning procedure was accomplished relatively quickly. With coarse tuning, a 2km, 0.76 μF, 11 kV cable was energised to $2U_0$ at 50 Hz and drew only 13 A from the supply. The VA supplied to the load exceeded the VA drawn from the supply by a factor of 20 to 30.

7 Acknowledgements

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